Polymers in Solar Energy Utilization

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FOREWORD

The ACS SYMPOSIUM SERIES was founded in 1974 to provide a medium for publishing symposia quickly in book form. The format of the Series parallels that of the continuing ADVANCES IN CHEMISTRY SERIES except that in order to save time the papers are not typeset but are reproduced as they are submitted by the authors in camera-ready form. Papers are reviewed under the supervision of the Editors with the assistance of the Series Advisory Board and are selected to maintain the integrity of the symposia; however, verbatim reproductions of previously published papers are not accepted. Both reviews and reports of research are acceptable since symposia may embrace both types of presentation.

PREFACE

THE SUN ALWAYS SHINES, even on cloudy days, and pours forth an enormous amount of energy onto the planet Earth. Obviously this solar energy is the cause of the basic meteorological phenomena that we observe daily, and the effect of solar storms and flares on electromagnetic communications systems is also well established. In the final analysis, solar energy is the ultimate source of most of the energy we use. For example, fossil fuels are residues of past animal and plant populations whose basic energy and growth were derived from the sun. Much of the current emphasis on renewable energy resources focuses on sources, such as wood, that store solar energy in some form. In addition, many of the proposed alternate energy sources (e.g., wind power) derive their basic energy from the action of solar energy on our planet. With the exception of nuclear energy, essentially all of our present energy sources are derived from the sun in one way or another. Even nuclear fusion is patterned after the basic mode of energy production in the sun.

Energy is consumed in almost every facet of our lives ranging from food production to recreation, and the energy demand will increase as the results of technology reach out to other portions of the world. Where will the necessary energy come from? Better utilization of solar energy is considered by many to be the best potential source of this needed energy. It has been estimated that all the energy needs of the United States in the year 2000 could be met if we could only harness and utilize the total solar energy that falls on about 15,000 square miles. This land area is less than 0.5% of the area of the United States and is equivalent to about one-tenth the area of California or about one-half the area of Indiana, Maine, or South Carolina.

Two major difficulties arise here, however: (1) the problem of how to harness or utilize this fairly diffuse and intermittent source of energy; and (2) the problem of storing this energy and/or transmitting it to another location where it is needed. Many approaches have been taken to solve both of these difficulties. In this book we will consider the use of polymeric materials in various methods of solar energy utilization. Although some overlap does occur, the 29 chapters in this book have been placed into three sections: General Solar Applications, Polymer Photodegradation in Solar Applications, and Photovoltaic and Related Applications.

Essentially, the 13 chapters in the first section consider the basic economics of solar energy, its collection by various devices, and the storage of the collected energy for short-term use. Chapters include a general survey of the various ways in which polymeric materials have been utilized in solar energy collection and of the problems as well as the potential of polymers in this application; basic economic considerations in solar heating systems with special emphasis on the role of plastics in cost reduction; descriptions of some solar collectors that utilize polymers with consideration of cost, effectiveness, and degradation; use of various polymeric materials for sealants; polymeric coatings on metal mirrors; and use of polymers in heat storage as liners in solar ponds in which water is the thermal storage medium, as well as the storage of thermal energy in the ground itself.

The basic conclusion of the first section is that polymers can be used advantageously in solar applications but that more research is needed. Probably the most pressing problem cited is that of photodegradation, which is the central topic of the seven chapters in the second section. Chapters in this section include theoretical models to predict the utility of a polymer in solar applications by examining the formation of polar groups on the polymer backbone chains—which would make the polymer more water sensitive and less suitable for solar applications, especially photovoltaic applications; the use of UV and fluorescent microscopy to follow photooxidation in some polymers; the use of a laser photoacoustic technique to compare actual outdoor degradation studies with those obtained in an accelerated test; and photodegradation studies of some specific polymers. For example, poly(*n*-butyl acrylate) degradation and its implications for solar applications are reported and a fairly successful attempt to reduce photodegradation in poly(methyl methacrylate) by the copolymerization of a monomer that contains a UV-screening agent is described. The final chapter of this section considers the effect of uniaxial or biaxial deformation in polyethylene films on the photodegradation. The seven papers in the second section, along with several in the first section, clearly show that photodegradation is a potential problem in any solar utilization of polymers. In addition, they provide some insights into methods of predicting this effect and possible ways to alleviate this difficulty.

Even though the efficiency of the processes may be lower than desired, the early chapters in this book, and other sources, clearly show that solar energy can be captured and utilized to some extent with our current technology. Enthusiasm in this area, however, must be tempered by the facts that storage of this captured energy is limited and that transmission of the solar-derived energy is even more problematic. Trapping the solar energy in some type of thermal storage system may suffice for short-term storage (e.g., for use at night or on rainy days) but cannot be used effectively for truly long-term applications. In addition, thermal energy has a very limited transmission or transportation range. More effective methods of energy storage and/or transmission would involve the conversion of the solar energy into some form of chemical energy (e.g., hydrogen) or into electricity. This problem is considered in the nine chapters of the third section.

Most of the chapters in the third section are concerned with photovoltaic (PV) applications (conversion of light into electrical energy). Because of the diffuse nature of solar energy, the photovoltaic collection devices must be very large or else the light that strikes them must be concentrated. The first chapter in this section gives an overview of luminescent solar concentrators that can be used with the PV collectors. Most PV collectors or modules are multilayered systems containing a photovoltaic cell element. The next four chapters consider the use of various plastics as encapsulant or pottant materials in the PV modules.

The majority of photovoltaic modules use silicon as the photovoltaic cell element, but other materials are, in principle, possible. The last four chapters consider the use of organic polymers (sometimes doped) as the cell element or in some related conducting property: acrylonitrile, some polymeric phthalocyanines; and polymers of 2-vinylnaphthalene that is doped with pyrene and 1,2,4,5-tetracyanobenzene. The study on the last group of polymers was initiated by the idea that they could be used to transfer solar energy to a reaction center and produce some type of chemical reaction. The final chapter carries this approach further in the consideration of polymeric electrodes that could be used to split water into oxygen and hydrogen. The latter could then be utilized as a source of storable, readily transportable chemical energy.

In summary, the 29 chapters in this book point out the vast potential of solar energy utilization and note the advantages and problems of using polymers in this application. Polymers clearly offer advantages in cost, weight, and the variety of materials available but do suffer from varying degrees of photodegradation. This book points out several areas of needed research, but it also shows the promise of an energy-rich future in which solar energy can be used directly as thermal energy or indirectly as solar-derived electricity or chemically stored energy (e.g., hydrogen derived via solar water splitting). This optimistic view is in marked contrast with many of the gloomy prognostications that abound in today's world, but such advances are well within the realm of possibility in the near future.

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CONTENTS

GENERAL SOLAR APPLICATIONS

Polymers in Solar Energy: Applications and Opportunities

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Polymers have many potential applications in solar technologies that can help achieve total system cost-effectiveness. For this potential to be realized, three major parameters must be optimized: cost, performance, and durability. Optimization must be achieved despite operational stresses, some of which are unique to solar technologies. This paper identifies performance of optical elements as critical to solar system performance and summarizes the status of several optical elements: flat-plate collector glazings, mirror glazings, dome enclosures, photovoltaic encapsulation, luminescent solar concentrators, and Fresnel lenses. Research and development efforts are needed to realize the full potential of polymers to reduce life-cycle solar energy conversion costs. Problem areas which are identified are the interactions of a material with or its response to the total environment; photodegradation; permeability/adhesion; surfaces and interfaces; thermomechanical behavior; dust adhesion; and abrasion resistance. Polymeric materials can play a key role in the future development of solar energy systems [1]. Polymers offer potentially lower costs, easier processing, lighter weight, and greater design flexibility than materials in current use.

Polymeric materials are used in all solar technologies. In addition to such conventional applications as adhesives, coatings, moisture barriers, electrical and thermal insulation, and structural members, polymers are used as optical components in solar systems. Mirrors on parabolic troughs are made up of metallized fluoropolymers and acrylics. Commercial flat-plate collectors are glazed with fluoropolymers and ultraviolet-stabilized polyester/glass fiber composites. Photovoltaic (PV) cell arrays are encapsulated with silicones and acrylics for protection from the weather. In laminated (safety glass) mirrors for central receiver heliostat systems, polyvinyl butyral is used as a laminating and encapsulating agent. Cast and molded acrylic Fresnel lenses are used to concentrate sunlight onto photovoltaic cells and thermal receivers. The widespread use of polymers is evident from the information displayed in Table I, where applications of polymers are listed for each major solar technology.

It is possible to estimate the amount of polymer which might be used in the optical elements of solar energy systems [1]. The estimate assumes a market penetration for solar systems equivalent to 0.4 Quads/year (U.S. 1980 energy use was about 85 Quads, 1 Quad = 10^{15} Btu) starting in the time period 1985-1995. A solar insolation of 1 kW/m^2 for about 6 hours per day will require an area penetration of 2 x 10^8 m^2/yr (82 $miles^2$/yr) or about 5500 metric tons per year per mil of thickness. An average thickness of 10 mils would require, for example, an appreciable fraction of the present market for either acrylics or polycarbonate. Presumably, considerably larger amounts of polymer could be used in non-optical structures but this is system specific and difficult to estimate. Calculations [1] also suggest that the present low level of funding for R&D on polymers implies an underestimation of the potential which polymers have for applications to solar systems.

The use of polymers in solar equipment will require major changes from past large-scale applications, especially in achieving satisfactory performance under all combinations of stress. Cost, performance, and durability must be optimized. If early cost-effective commercialization of solar energy is to be realized, critical delays must be shortened. Service experience has traditionally guided the evolution of systems toward an optimum design. The process can be hastened by applying all available understanding of the basic behavior of materials in the initial designs of equipment. The stalemate imposed by the lack of market and supply of solar systems can be broken by government-supported development of technology that demonstrates the economic viability of new or modified materials. Such development would enable materials suppliers and manufacturers of solar equipment to make knowledgeable business decisions and reduce development cost and time.

Applications

The optical elements of solar systems are important applications for polymers. The use of polymers for optical elements will, however, impose several unusual material requirements. Five examples of the current development of polymeric optical elements are considered below. Problems such as dirt accumulation and photodegradation, which are common to most optical elements, are considered in a later section. More conventional applications are then noted very briefly.

Table I.

Solar Energy System	Polymer Application: Mirror Glazings	Flat-Plate Glazings	Encapsulation	Seals/Adhesives	Structural Members	Heat Transfer/ Energy Storage	Paints/Coatings	Piping	Thermal & Electrical Insulation	Moisture Barriers	Fresnel Lenses	Membranes
Solar thermal conversion	x	x	x	x	x		x	x	x	x	x	
Photovoltaics	x	x	x	x	x	x	x		x		x	
Solar heating and cooling of buildings	x	x	x	x	x		x	x	x	x	x	
Wind				x	x	x	x		x			
Ocean thermal				x	x		x	x	x	x		
Biological/chemical		x		x	x	x	x		x	x		x